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Energy end-use and grid interaction analysis of solar assisted ground source heat pumps in Northern Canada

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Abstract

This paper presents an analysis conducted on a ground source heat pump (GSHP) system coupled with evacuated tube solar thermal collectors to reduce the borefield size in Northern Canada. The annual energy consumption, utility costs, grid impact, greenhouse gas emissions, and economics of a solar assisted GSHP system are compared to several conventional and heat pump (HP) space heating, cooling and domestic hot water systems for mid-rise apartment buildings located in Whitehorse, YK and Yellowknife, NT. In both regions the solar assisted GSHP system demonstrated energy savings over a conventional space heating system, while successfully overcoming an annual ground energy imbalance and reducing the required borefield size. From a grid perspective, although the HP systems shifted the space heating fuel source from fuel oil to electricity, the solar thermal system is able to help minimize the use of inefficient auxiliary heat to meet the space heating loads. The high associated capital costs of a GSHP system coupled with a solar thermal system make the economics difficult to justify; however for regions where energy security is of high importance, the energy savings achieved with these systems can have a substantial impact.

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Keywords: Solar Thermal, Ground source heat pumps, Northern climate, Mid-rise apartment

1. Introduction

The residential sector in Canada accounts for 17% of national secondary energy use, with over 80% of this total directed towards space heating, space cooling, and domestic hot water (DHW) [1]. Apartment buildings comprise

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22% of the total floor area within this sector [1], and thus represent a prime opportunity for deep energy reductions. While significant research has focused on the role of the building envelope in energy efficient design, there has been less attention paid to the importance of the improving the efficiency of the mechanical system. The task of designing an appropriate mechanical system to meet building thermal loads is a complex one and is highly dependent on building design, use, and climate. The cost and time intensive nature of this task often results in designers selecting a system they are most familiar with, despite potentially higher energy use.

While ground source heat pumps (GSHP) are well known for their strong energy savings potential, the high costs associated with borefield drilling often dissuade designers from using this type of system. These costs are particularly pronounced in heating dominated climates, where a large imbalance between heating and cooling loads requires a significant borefield depth to minimize a systematic decline in ground temperatures over time. Solar assisted ground source heat pumps (SAGSHP) have been proposed in the literature [2, 3 and 4] as a means of replenishing the borefield and reducing required borehole depths. However, little work has been done to date on the benefits of these systems in extreme cold climates, such as those in Northern Canada (north of 60th parallel).

This paper presents a viable concept for high performance building design in the Canadian North. A novel system is proposed combining a ground source heat pump with evacuated tube solar collectors in order to reduce borefield size and costs. The system is integrated into energy efficient multi-unit residential buildings in Whitehorse, YT and Yellowknife, NT. System performance in terms of costs, energy use, and GHG emissions are compared to conventional oil-fired boiler and heat pump systems. Results are also examined from a grid perspective to determine potential grid impacts when converting from oil to electric based heating, which must also be taken into account in these two regions.

2. Methodology and simulation

To perform the analysis an energy model of a 32 unit mid-rise apartment was developed using the TRNSYS simulation tool [5]. The shape and dimensions of the apartment were taken from the DOE Benchmark models [6] and the building envelope was adapted to the respective requirements for each region's climate zone [7]. The apartment is four stories, with 8 apartment suites and a corridor on each floor. The total apartment heated floor area is 3,135 m² with a footprint area of 784 m². A schematic and floor plan of the mid-rise apartment is shown in Fig. 1.

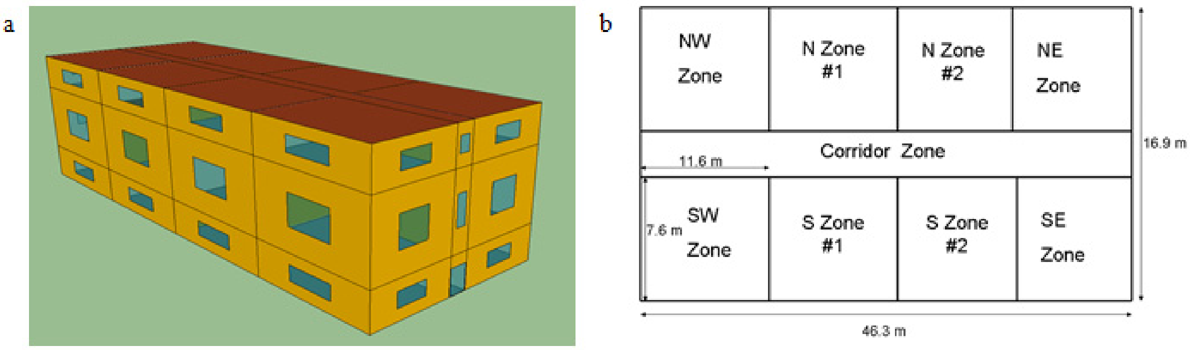

Fig. 1. (a) 3D model; (b) Floor plan of mid-rise apartment

The apartment suites are maintained between 21°C and 23°C, with relative humidity above 30%. Approximately 33 L/s of fresh air is delivered to each apartment suite preconditioned with a 50% effectiveness heat recovery ventilator. Lighting, occupancy and receptacle schedules were assumed to follow those outlined by the National Energy Code for Buildings [7] and a hot water draw profile assumed to follow that of IEA Annex 42 [8] for Canada (approximately 184 L of hot water per day per apartment suite). The Whitehorse and Yellowknife energy models were run using the respective CWEC weather file. The most recent published residential electricity rates (~$38.9 CDN/GJ for Whitehorse [9] and ~$83.3 CDN/GJ for Yellowknife [10]) and the region specific 2014 historical oil rates (~$32.4 CDN/GJ [11]) were used to estimate the building's annual utility cost. GHG emissions were estimated based on the emission factors from the region's respective electricity generation source (primarily hydro with diesel generators for back-up and peaking) and the equivalent fuel oil factor [12] summarized in Table1 below.

Table 1. Electricity and fuel oil GHG emission factors for Whitehorse and Yellowknife

Region	Electricity GHG emission factor	Fuel Oil GHG emission factor
Whitehorse	48.5 g CO_2/kWh	2,735 g CO_2/L
Yellowknife	123.9 g CO_2/kWh	2,735 g CO_2/L

To perform an analysis on the impact solar thermal energy collection can have on meeting the apartment space heating and DHW loads, five heating, cooling and DHW systems were considered for comparative analysis.

2.1. Scenario 1: Oil fired hydronic heating, packaged terminal air conditioning and electric DHW (Base Case)

Each apartment suite is conditioned with a packaged terminal air conditioning unit with a hydronic heating coil. The heating coils are served by an 83.3% thermal efficient oil fired boiler sized to meet the peak building heating load. The heating and cooling capacities are modulated to maintain the desired temperature setpoint with part load performance of the heating and cooling equipment estimated from DOE performance curves [13]. Each apartment suite has its own 110 L electric DHW heater to meet the DHW loads. In both regions, space heating is the highest energy end use representing 50% of the energy consumption, while DHW heating represents the second highest at approximately 15% and space cooling the least at approximately 2%. A schematic of the system is shown in Fig. 2.

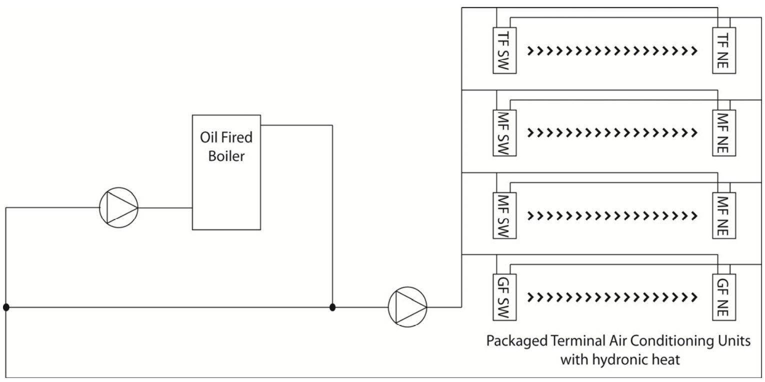

Fig. 2. Base case heating and cooling schematic

2.2. Scenario 2: Cold climate air source heat pump and electric DHW (CC ASHP)

A second reference system is considered, in which cold climate air source heat pumps (CC ASHP) (air to air) are used to meet the space conditioning loads. CC ASHPs were selected as these systems are able to maintain their capacity and performance at lower ambient temperatures through the use of variable capacity compressors. Conventional air source heat pump system heating capacities and performance degrade substantially at low ambient temperatures and thus would not be a suitable choice for the sub-arctic regions as auxiliary electric space heating would constantly be required. The added benefit of the selected CC ASHP is that with the variable capacity compressor, the system can efficiently modulate to maintain space temperature set points rather than cycling on-off.

The CC ASHP selected for the analysis has a rated heating capacity of 11.1 kW and coefficient of performance (COP) of 1.8 at an ambient temperature of -12.8°C [14]. The CC ASHP can also operate down to a temperature of -35°C, achieving a heating capacity of 6.0 kW with a COP of 1.0. With the mid-rise apartment suites having a peak heating load between 5 to 7 kW at -41°C, the heat pump is well sized to efficiently meet the space heating loads the majority of the time. At warmer ambient temperatures, the variable capacity compressor of the heat pump permits modulation down to 40% of the rated heating capacity to meet the load without having to cycle on-off. The part-load performance of the heat pump was estimated from the inverter compressor type heat pump testing data published by the Swedish Energy Agency [15]. A back-up electric duct heater sized to meet the peak heating load is also installed in each apartment suite. Each apartment suite has its own 110 L electric DHW heater to meet the DHW loads.

2.3. Scenario 3: Ground source heat pump and electric DHW (GSHP)

The third heating and cooling system evaluated is a ground source heat pump system (GSHP), where the thermal energy stored in the ground is upgraded through water to air heat pumps located in each apartment suite to meet the space conditioning loads. As the ground remains at a fairly stable temperature, the GSHP system can be an efficient method of meeting the space heating loads, as long as the ground borefield is sized sufficiently to overcome the heat extraction and heat injection imbalance. With the two Northern regions, the space cooling loads are very low, which ultimately results in an extremely large borefield in order to overcome the annual energy imbalance. The borefield was sized following the Kavanaugh and Rafferty equation [16] taking into account the annual imbalance, peak monthly ground load and peak hourly ground load for both regions. The estimated borefield sizes for the mid-rise apartment in Whitehorse and Yellowknife are summarized Table 2.

Table 2. Electricity and fuel oil GHG emission factors for Whitehorse and Yellowknife

Region	Borefield Configuration	Borehole Length	Borehole Spacing
Whitehorse	15 x 4	108.2 m	6.1 m
Yellowknife	16 x 4	88.7 m	6.1 m

The apartment suite water to air heat pumps were sized to meet the peak heating load with an entering fluid temperature of -3.8°C. A back-up electric boiler is also installed to inject energy into water loop in the event fluid temperatures fall below -3.8°C and the apartment suite water to air heat pumps are unable to meet the space heating load. Future work will look into different auxiliary heat strategies such as a fuel oil boiler or a cascade heat pump system. The heat pumps have a rated COP of 3.8 at the design entering fluid temperature not including fan power [17]. The ground soil properties for Whitehorse and Yellowknife were taken from ground and terrain studies done in each respective region [18, 19]. Each apartment suite has its own 110 L electric DHW heater to meet the DHW loads. A schematic of the system is shown in Fig. 3.

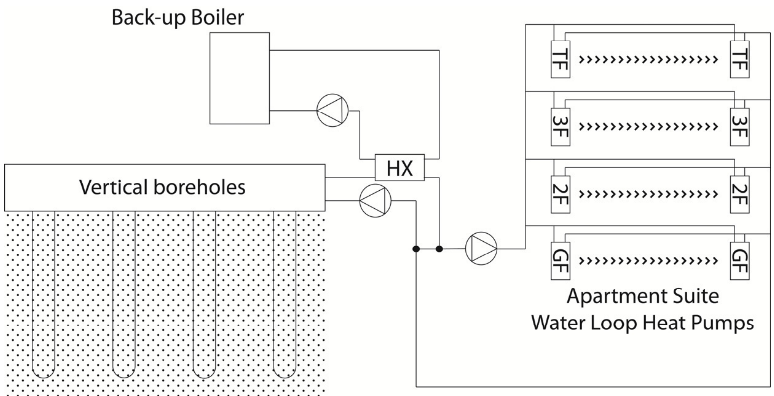

Fig. 3. GSHP heating and cooling schematic

2.4. Scenario 4: Solar assisted ground source heat pump and electric DHW (SA GSHP)

To overcome the large imbalance in the ground heating and cooling loads, a solar assisted GSHP is investigated where the solar energy collected from roof-top evacuated tube solar collectors is injected into the borefield to help reduce the ground energy imbalance between heat extraction and heat injection. Performance characteristics of the selected evacuated tube solar collector [20] were taken from the Directory of Certified Solar Collector Ratings [21]. For the Whitehorse region, three south facing rows of 20 collectors were specified at a fixed slope of 45° to maximize summertime collection for a total solar collector area of 257.2 m². For Yellowknife, only two rows of 20 south facing collectors were specified at a slope of 47° due to the minimal added benefit of a third row because of shading. For Yellowknife the total solar collector area is 171.5 m². The borefield sizes were estimated by taking into account the amount of solar energy that could be injected into the ground to offset the peak monthly ground load and the help reduce the annual ground imbalance. For Whitehorse, a 17.5% borefield size reduction is estimated while a 5% reduction is achieved for Yellowknife. Although both regions receive a similar amount of horizontal solar radiation on an annual basis (3.75 GJ/m²/year), the larger solar collector surface area and more suitable ground properties in Whitehorse allows for a larger reduction in the borefield size. The thermal energy from the solar collectors is first stored in a 10,000 L storage tank and then injected into the borefield through a plate frame heat exchanger when the temperature difference was beneficial. The same apartment suite water to air heat pumps specified in scenario 3 are used in this proposed system as well as the same apartment suite electric DHW tanks. A schematic of the system is shown in Fig. 4. Future work will optimize system components such as using flat plate collectors instead of evacuated tube and reducing the solar storage tank volume (if required at all) as well as where in the loop the solar energy is injected.

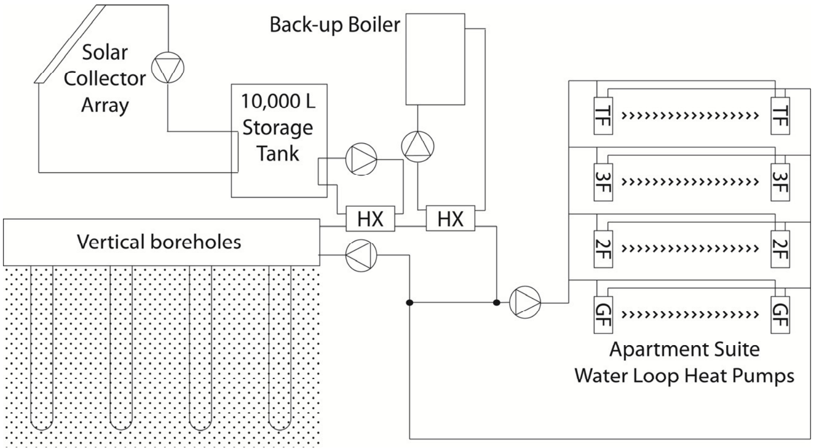

Fig. 4. SA GSHP heating and cooling schematic

2.5. Scenario 5: Ground source heat pump with solar domestic hot water (GSHP w. SDHW)

To further determine whether the use of solar energy to reduce the annual ground imbalance is a good strategy, a fifth system is proposed where evacuated tube solar collectors are used to meet a portion of the domestic hot water load. Using the GSHP system proposed in scenario 3, the solar thermal system proposed in scenario 4 for each region is added to meet a portion of the domestic hot water load. Domestic hot water is preheated in a 3,300 L storage from the thermal energy from the solar collectors and each apartment suite is equipped with a booster heater to maintain a 60°C domestic hot water temperature. The thermal energy from the solar collectors is first stored in a 10,000 L tank and the energy is transferred when there is a beneficial temperature difference between the two storage tanks. A schematic of the system is shown in Fig. 5. It should be noted that the solar energy is not injected into the borefield in this system, and thus the solar energy could be circulated directly to the DHW storage tank. The value added of the 10,000 L storage tank will be evaluated in future work.

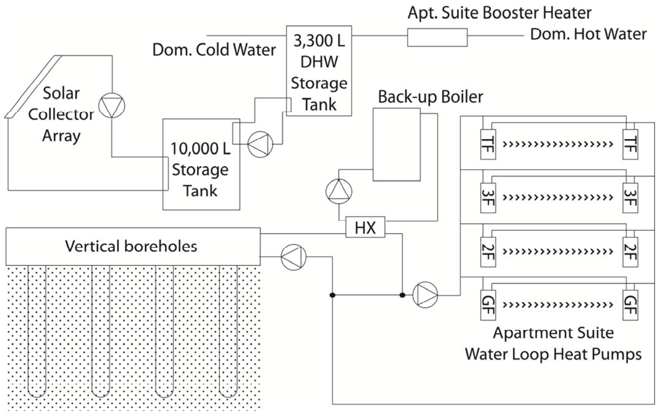

Fig. 5. GSHP with solar DHW heating and cooling schematic

3. Results

Each simulation was run over a 5 minute timestep and the GSHP system simulations were run for a period of 5 years to take into account to take into the depletion of ground energy over time and the subsequent demand for more auxiliary heat to meet the space heating loads. The year 5 results of these systems are presented.

3.1. Energy, utility cost and GHG emissions

The annual energy consumption and peak electrical draw, utility costs and GHG emissions of all systems analyzed are summarized in Tables 3, 5 and 7 for Whitehorse, respectively and Tables 4, 6 and 8 for Yellowknife, respectively. The annual space heating system COP is also summarized in Table 3 and Table 4 for the Whitehorse and Yellowknife region, which includes the associated compressor power and any auxiliary heat required to meet the space heating load.

Table 3. Annual mid-rise apartment energy consumption and peak electrical draw for Whitehorse

Energy	Base Case	CC ASHP	GSHP	SA GSHP	GSHP w. SDHW
Electricity (GJ)	1,593.7	2,310.2	1,977.6	1,868.6	1,653.5
Fuel Oil (GJ)	1,573.0	0.0	0.0	0.0	0.0
Total (GJ)	3,166.7	2,310.2	1,977.6	1,868.6	1,653.5
Intensity (GJ/m²)	1.01	0.74	0.63	0.60	0.53
Peak Electric Draw (kW)	93.8	226.4	172.7	155.7	171.3
Annual Heating COP	--	1.30	2.65	4.15	2.45

Table 4. Annual mid-rise apartment energy consumption and peak electrical draw for Yellowknife

Energy	Base Case	CC ASHP	GSHP	SA GSHP	GSHP w. SDHW
Electricity (GJ)	1,690.5	2,505.4	2,202.3	2,018.2	1,903.6
Fuel Oil (GJ)	1,714.3	0.0	0.0	0.0	0.0
Total (GJ)	3,404.8	2,505.4	2,202.3	2,018.2	1,903.6
Intensity (GJ/m²)	1.09	0.80	0.70	0.64	0.61
Peak Electric Draw (kW)	91.1	192.2	157.6	143.0	152.3
Annual Heating COP	--	1.22	1.91	3.38	1.79

Table 5. Annual mid-rise apartment utility cost for Whitehorse

Utility Cost	Base Case	CC ASHP	GSHP	SA GSHP	GSHP w. SDHW
Electricity ($, CDN)	$66,850	$95,852	$82,257	$77,874	$69,534
Fuel Oil ($, CDN)	$54,578	$0	$0	$0	$0
Total ($, CDN)	$121,428	$95,852	$82,257	$77,874	$69,534

Table 6. Annual mid-rise apartment utility cost for Yellowknife

Utility Cost	Base Case	CC ASHP	GSHP	SA GSHP	GSHP w. SDHW
Electricity ($, CDN)	$149,677	$218,500	$192,901	$177,358	$167,676
Fuel Oil ($, CDN)	$59,221	$0	$0	$0	$0
Total ($, CDN)	$208,898	$218,500	$192,901	$177,358	$167,676

Table 7. Annual mid-rise apartment GHG emissions for Whitehorse

Utility Cost	Base Case	CC ASHP	GSHP	SA GSHP	GSHP w. SDHW
Electricity (tons CO_2 eq.)	22.3	32.4	26.6	25.2	22.3
Fuel Oil (tons CO_2 eq.)	111.1	0.0	0.0	0.0	0.0
Total (tons CO_2 eq.)	133.4	32.4	26.6	25.2	22.3

Table 8. Annual mid-rise apartment GHG emissions for Yellowknife

Utility Cost	Base Case	CC ASHP	GSHP	SA GSHP	GSHP w. SDHW
Electricity (tons CO_2 eq.)	60.5	89.7	75.8	69.5	65.5
Fuel Oil (tons CO_2 eq.)	121.0	0.0	0.0	0.0	0.0
Total (tons CO_2 eq.)	181.5	89.7	75.8	69.5	65.5

From the results it can be seen that in both regions the peak electrical demand increases over the base case scenario, which is expected since the largest energy end use is now being met with an electricity based heating system. The elimination of fuel oil as the space heating fuel source results in significant reductions in GHG emissions as the cleaner electricity production is used to meet this load in both regions. Using solar thermal energy to minimize the annual ground imbalance helps reduce the use of auxiliary heat to meet the space heating loads; however the improvement in the annual heating system COP was not as beneficial as using the solar energy to meet a portion of the DHW load. This result can be expected however, as with the efficient GSHP space heating system, the DHW load represents the highest energy consumption and using the solar thermal energy to reduce this load has a larger impact. The solar thermal energy is also used to directly meet the domestic hot water energy use, whereas in the SA GSHP system the solar energy is used to provide supplemental energy to the GSHP system to meet the space heating loads. The use of solar energy to help meet the space heating load is likely to have a greater benefit in building types where the DHW consumption is low such as an office or school. It is also interesting to note that with the solar DHW systems the tank heat loss does not contribute to meeting the apartment suite heating loads, thus increasing the annual ground energy extraction. This results in a higher use of the auxiliary heating system as seen by the decrease in the annual system heating COP in both regions. This is further highlighted when comparing the annual ground energy imbalance of all three GSHP systems assessed after 5 years of operation (Table 9).

Table 9. Borefield annual heat transfer

Region	GSHP	SA GSHP	GSHP w. SDHW
Whitehorse	-294.5 GJ	68.1 GJ	-300.6 GJ
Yellowknife	-126.8 GJ	34.9 GJ	-137.6 GJ

In both the conventional GSHP system and the GSHP system with solar DHW, there is a net annual heat extraction from the borefield, which will result in a gradual reduction in ground temperatures and a continued increase in auxiliary heat to meet the space heating loads. For the solar assisted GSHP system, there is a net energy injection and thus the requirement of auxiliary heat to meet space heating loads will be further reduced on an annual basis and highlights a suitable method to ensure the ground energy is not depleted over time.

3.2. Simple payback period and 20 year life cycle cost

To estimate the simple payback period and 20 year life cycle cost, the incremental and maintenance cost of each heat pump and solar thermal system was estimated from RSMeans [22] and contractor surveys for the specific region. Borefield drilling costs of $80/m were assumed [23].

The 20 year life cycle cost is calculated summing the incremental capital cost to the present worth of the annual utility costs over 20 years and the annual maintenance costs. To calculate the present worth for the utility and maintenance costs, an inflation rate of 1.5% and a discount rate of 4% were assumed based on the current Canadian financial market. The residential electricity and fuel oil escalation rates for Whitehorse and Yellowknife were obtained from the National Energy Board [24] – 1.2% and 0.4% for Whitehorse, respectively and 0.7% and 0.4% for Yellowknife, respectively. The maintenance and fixed utility costs were assumed to follow the inflation rate. It is assumed that all the equipment has a 20 year lifespan and no major maintenance costs occur during the 20 year life cycle. The estimated simple payback period and 20 year life cycle cost for each system is summarized in Table 10 for Whitehorse and Table 11 for Yellowknife.

Table 10. Simple payback period and 20 year life cycle cost for Whitehorse

Metric	Base Case	CC ASHP	GSHP	SA GSHP	GSHP w. SDHW
Simple Payback Period (Years)	--	11.0	19.6	24.0	22.5
20 Year Life Cycle Cost ($000, CDN)	$2,193	$2,111	$2,399	$2,622	$2,616

Table 11. Simple payback period and 20 year life cycle cost for Yellowknife

Metric	Base Case	CC ASHP	GSHP	SA GSHP	GSHP w. SDHW
Simple Payback Period (Years)	--	>40	>40	30.9	24.4
20 Year Life Cycle Cost ($000, CDN)	$3,483	$3,878	$3,950	$4,001	$3,891

Analyzing the economic results for Whitehorse, it can be seen that of the systems analyzed the CC ASHP system was the most suitable, having an 11 year simple payback period and the lowest 20 year life cycle cost. It should be noted however that the peak electrical demand of the cold climate air source heat pump system far exceeds the base case and ground source heat pump system, which needs to be taken into account if the local electricity grid is already strained. While the GSHP has improved utility cost and energy savings, the higher associated cost of the borefield cannot overcome the low cost of the utility rates as seen by the 19.6 year simple payback period and higher 20 year life cycle cost. While using solar thermal energy to reduce the use of auxiliary heat to meet the desired loop temperature, the higher associated cost of the evacuated tube solar collectors results in an increased simple payback period and 20 year life cycle cost over a conventional GSHP system. Further analyzing the use of solar energy, as anticipated, using solar energy to meet a portion of the domestic hot water load demonstrated the best economics of the GSHP systems, as the highest energy end use is being addressed with the renewable energy source.

For Yellowknife, a different conclusion can be drawn as the cold climate air source heat pump system was found to be unsuitable. The higher electricity costs for the Yellowknife region and ultimate higher capital costs of the cold climate air source heat pump, results in the system having the highest 20 year life cycle cost of all systems evaluated and an infinite payback period. For the GSHP system, annual utility cost savings were achievable due to the higher efficiency system; however the requirement of using an auxiliary heating source to compensate for the annual ground energy imbalance, results in a simple payback period above 40 years. Using solar energy to help overcome the borefield annual energy imbalance demonstrated a benefit over the conventional GSHP system; however the high cost associated with the evacuated tube solar collectors and borefield still results in a simple payback period above 30 years. The lowest simple payback period of 24.4 years was achieved using the solar energy to preheat the domestic hot water, highlighting that the solar energy is better off utilized to meet a portion of the domestic hot water heating load, than offsetting the auxiliary heat for this building type.

3.3. Grid analysis

The characteristics of the heating systems extend beyond the building envelope to impact the connected electrical grid through their power and energy consumption. Peak power consumption is of particular concern to electric utilities, as its grid must be able handle peak demand, even if only for a few hours of the year. New demand may require expensive capacity investments, from wires and substations to electric generators. It may also require the use of more peaking plants, commonly fossil fuel (diesel). Energy consumption, discussed prior, can impact drawdown from limited hydro supplies and increase reliance on more expensive and polluting fossil generation.

Load duration curves, revealing the number of hours per year power consumption exceeds a given level, can give some idea of impact; these are provided for Whitehorse (Fig. 6a.) and Yellowknife (Fig. 6b.). In these figures, it is seen that using CC ASHPs to meet the space heating load results in a change in peak double that of the GSHP alternatives. In grids operating close to margins, where many of these systems are being considered, this may be cause for concern. Taking this into account, GSHP and its variations may have a lesser impact on the grid. Note that they also have different peak profiles than CC ASHP, which maybe something to consider in the aggregate.

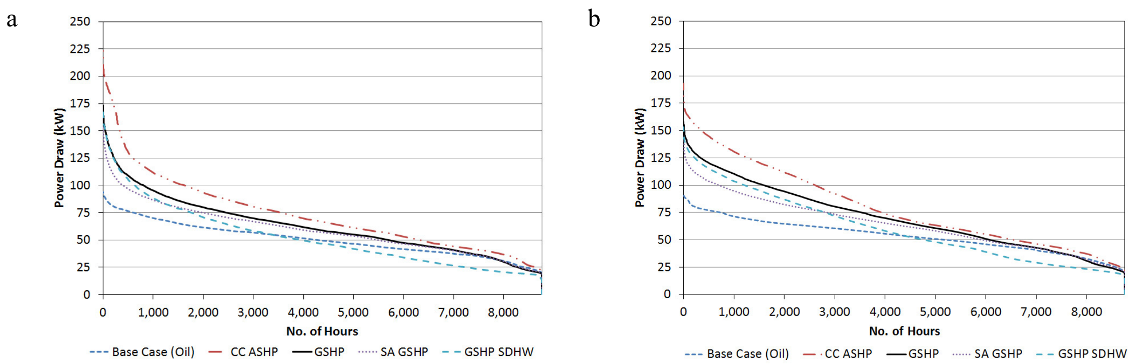

Fig. 6. (a) Load duration curve Whitehorse (b) Load duration curve Yellowknife

4. Conclusion and future work

An analysis has been presented on the potential benefit of using solar thermal energy to overcome the annual ground energy imbalance for ground source heat pump systems in the Canadian North. The assessment was performed on a newly constructed mid-rise apartment located in Whitehorse and Yellowknife designed to meet the minimum efficiency requirement of the National Energy Code for Buildings. The analysis involved comparing the annual energy consumption, annual utility costs, annual GHG emissions, simple payback period and the 20 year life cycle cost for five different space heating, cooling and DHW systems for each region – a conventional oil fired hydronic heating system, a cold climate air source heat pump, a ground source heat pump, a solar assisted ground source heat pump and a ground source heat pump with a solar DHW system. The results showed that in both regions significant energy, utility cost and GHG emission reductions can be achieved with heat pump systems; however the high associated capital costs and low utility rates in the Northern regions challenge the economic viability of these systems. The use of solar energy to effectively overcome the annual ground energy imbalance of a ground source heat pump system was demonstrated as the net annual borefield heat transfer was positive, helping to reduce the need for auxiliary heat, while reducing the required borefield size by 17.5% in Whitehorse and 5% in Yellowknife. Using the solar energy to meet the domestic hot water load proved to be more economical as the solar energy is used to meet the highest energy end use after an efficient ground source heat pump system meets the space heating demand. From a grid perspective, shifting the space heating energy source from fuel oil to electricity increases each building's electrical demand, which can be of concern. The cold climate air source heat pump systems, although economically viable in Whitehorse, results in a peak demand double of the base case, which must be taken into account. The ground source heat pump systems had a lesser impact, especially the solar assisted system, which is able to mitigate the use of auxiliary back-up heat due to an imbalance in ground energy.

The analysis highlights the potential solar energy has in successfully implementing a highly efficient ground source heat pump in Canada's far north by overcoming the annual ground energy balance. Future work will focus on optimizing the system by evaluating the use of flat plate solar collectors instead of evacuated tube collectors to inject the solar energy into the borefield in addition to different ground storage systems and alternative building types.

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